Construction and Building Materials 23 (2009) 1999–2006

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

The effects of using lime and styrene–butadiene–styrene on moisture sensitivity resistance of hot mix asphalt

Baha Vural Kok *, Mehmet Yilmaz

Firat University, Civil Engineering Department, 23169 Elazig, Turkey

ARTICLE INFO

Article history:
Received 4 December 2007
Received in revised form 25 August 2008
Accepted 27 August 2008
Available online 9 October 2008

Keywords:
Moisture damage
Modified bitumen
Lime
Retained Marshall stability
Indirect tensile strength

ABSTRACT

This study focuses on determining the effects of styrene–butadiene–styrene (SBS) and using mineral filler with lime on various properties of hot mix asphalt especially moisture damage resistance. The asphalt cement was modified with 2%, 4% and 6% SBS. The lime treated mixtures containing 2% lime by weight of the total aggregate as filler. The physical and mechanical properties of polymer modified binder and binder–aggregate mixes were evaluated through their fundamental engineering properties such as dynamic shear rheometer (DSR), rotational viscosimeter (RV) for binders, Marshall stability, stiffness modulus, indirect tensile strength and moisture susceptibility for mixes. The retained Marshall stability (RMS) and tensile strength ratio (TSR) values were calculated to determine the resistance of mixtures to moisture damage. To investigate clearly the effective of SBS and lime seven freeze–thaw cycle was applied to specimens at TSR test. The results indicate that application of SBS modified binders and lime as mineral filler one by one improves the stability, stiffness and strength characteristic of hot mix asphalt. According to retained Marshall stability it is concluded that addition of only 2% lime have approximately same effect with addition of 6% SBS. Using lime together within the SBS modified mixes exhibit high accordance and exacerbates the improvement of properties. Specimens containing both 2% lime and 6% SBS, have the highest stiffness modulus which is 2.3 times higher than those of the control mixture and showed the least reduction in tensile strength ratio while maintaining 0.70 tensile strength ratio after seven freeze–thaw cycle.

1. Introduction

Moisture damage and permanent deformation are the primary modes of distresses in hot mix asphalt (HMA) pavements. The performance of HMA pavements is related to cohesive and adhesive bonding within the asphalt–aggregate system. The loss of cohesion (strength) and stiffness of the asphalt film, and the failure of the adhesive bond between aggregate and asphalt in conjunction with the degradation or fracture of the aggregate were identified as the main mechanisms of moisture damage in asphalt pavements [1]. The loss of adhesion is due to water leaking between the asphalt and the aggregate and stripping away the asphalt film. The loss of cohesion is due to the softening of asphalt concrete mastic. Moisture damaged pavement may be a combined result of these two mechanisms. Further the moisture damage is a function of several other factors like the changes in asphalt binders, decreases in asphalt film thickness, changes in aggregate quality, increased widespread use of selected design features, and poor quality control [2,3]. Moisture susceptibility of hot mix asphalt (HMA) pavements continues to be a major pavement distress. As moisture damage reduces the internal strength of the HMA mix, the stresses generated by traffic loads increase significantly and lead to premature rutting, raveling and fatigue cracking of the HMA layer [4].

Additives have been used for improving performance of HMA pavements to various distresses (i.e., permanent deformation, moisture damage, and fatigue or low-temperature cracks). There are numbers of different additives available, which can be introduced directly to the asphalt cement (AC) as a binder modifier, or can be added to the mixture with the aggregate [5]. The use of hydrated lime or other liquid anti-stripping agents are the most common methods to improve the moisture susceptibility of asphalt mixes. Lime enhances the bitumen–aggregate bond and improves the resistance of the bitumen itself to water-induced damage. Researches have indicated that the amount of hydrated lime needed to improve the moisture sensitivity of hot mix asphalt is 1–2% by dry weight of aggregate [6,7]. Some mixture may require lime contents as high as 2.5% to achieve the desired results [8]. The studies showed that the hydrated lime appeared to perform better than liquid antistrip agents and indicated that the antistripping additives showed significant effect on reducing moisture damage [9,10].

Polymers, which are the most commonly used additives in binder modification, can be classified into four main categories, namely plastics, elastomers, fibres and coatings. To achieve the goal of improving bitumen properties, a selected polymer should

* Corresponding author. Tel.: +90 4242370000x5418.
E-mail address: bvural@firat.edu.tr (B.V. Kok).

0950-0618/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.conbuildmat.2008.08.019

create a secondary network or new balance system within bitumens by molecular interactions or by reacting chemically with the binder. The formation of a functional modified bitumen system is based on the fine dispersion of polymer in bitumen for which the chemical composition of bitumens is important [11]. Among polymers, the elastomer styrene–butadiene–styrene (SBS) block copolymer is the most widely used one. It has been identified that styrene–butadiene–styrene (SBS) triblock copolymer can obviously improve the mechanical properties of mixtures such as ageing [12], permanent deformation [13,14], low temperature cracking [15], moisture damage resistance [16,17], and so on.

Researchers have carried out laboratory experiments related to the effects of styrene–butadiene–styrene and lime on the moisture susceptibility of asphalt concrete mixtures. However limited experimental studies have been conducted for evaluating the effect of usage of SBS and lime together on the water damage of hot mix asphalt. In this study, the usage of SBS at various percentage (2%, 4% and 6% by weight of bitumen) and lime (2% by weight of aggregate) together in HMA and their effects on mechanical properties of hot mix asphalt especially moisture damage resistance were investigated. Also effects of SBS and lime on these properties of mixtures were compared. The physical and mechanical properties of polymer modified binders and binder–aggregate mixes were evaluated with conventional tests such as penetration, softening point and Fraass breaking point, rotational viscosity (RV) and dynamic shear rheometer (DSR) tests for binders, indirect tensile strength, Marshall stability and stiffness modulus tests for mixtures.

2. Materials

An asphalt cement, B 100–150 obtained from Turkish Petroleum Refineries was used as binder for mixture preparation. The asphalt was also modified with SBS (Kraton D 1101) manufactured by Shell Chemical Co. The properties of the Kraton D 1101 polymer are presented in Table 1. Three levels of SBS content were used, namely 2%, 4% and 6% by weight of bitumen. The SBS modified bitumens were prepared by using the propeller mixer. The asphalt binder was heated to 150 °C for 1 h and then subjected to 1.5 h of mixing time with SBS at 175 °C and 500 rpm shear rate. The physical properties of neat and modified asphalts are given in Table 2.

Limestone aggregate was used for the asphalt mixtures. Limestone is known as an alkaline aggregate hence it exhibits good adhesion with bitumen [18]. A crushed coarse and fine aggregate, with maximum size 19 mm, were selected for a dense-graded asphalt mixture. The grading curves of the aggregate mixtures are shown in Fig. 1. Hydrated lime, 2% by weight of aggregate was used as filler in lime treated mixtures. The physical properties of aggregate and lime are given in Table 3.

The mix design of the straight asphalt mixtures was conducted by using the standard Marshall mix design procedure with 75 blows on each side of cylindrical samples (10.16 cm in diameter and 6.35 cm thick). Marshall samples were compacted and tested by deploying the following standard procedures: bulk specific gravity (ASTM D2726), stability and flow test (ASTM D1559), and maximum theoretical specific gravity (ASTM D2041). The optimum binder content was found to be 5.2% by weight of aggregate for the unmodified asphalt mixes. An optimum binder content of 5.2% was chosen for all mixtures so that the amount of binder would not confound the analysis of the test data. For the Marshall stability and flow test and indirect tensile stiffness modulus test, the specimens were compacted by using 75 blows on each side of cylindrical samples at 4 ± 0.5% air void. As for the indirect tensile strength test the specimens were compacted in order to have 6–8% air void.

In this study the specimens were classified into four groups. The first group is the control specimens (C) prepared with neat bitumen. The second group of specimens prepared with modified bitumen consist of 2%, 4%, 6% SBS and were represented by S2, S4, S6, respectively. The third group of specimens, prepared with

Table 1
The properties of Kraton D 1101 polymer

Composition	Kraton D 1101
Molecular structure	Linear
Styrene/rubber ratio	31/69
Specific gravity	0.94
Tensile strength at break (MPa)	31.8
Shore hardness (A)	71
Physical form	Porous pellet, powder
Melt index	<1
Elongation at break (%)	880

Table 2
Fundamental properties of neat and SBS modified asphalts before and after short term aging

Properties	Standard	Binder types			
		B 100–150	B 100–150 + 2% SBS	B 100–150 + 4% SBS	B 100–150 + 6% SBS
Penetration (0.1 mm), 100 g, 5 s	ASTM D5	128	97	74	62
Softening point (°C)	ASTM D36	43.8	51.3	58.1	64.0
Fraass breaking point (°C)	IP 80	−19	−19	−21	−20
Penetration index (PI)	–	−0.37	0.94	1.71	2.38
After RTFOT					
Mass loss (%)	ASTM D2872	0.53	0.48	0.46	0.39
Penetration (0.1 mm), 100 g, 5 s	ASTM D5	73	61	50	43
Retained penetration, (%)		57	63	68	69
Softening point (°C)	ASTM D36	51.2	58.7	63.9	68.8
Increase in softening point (°C)		7.4	7.4	5.8	4.8
Penetration index (PI)	–	0.05	1.29	1.78	2.25

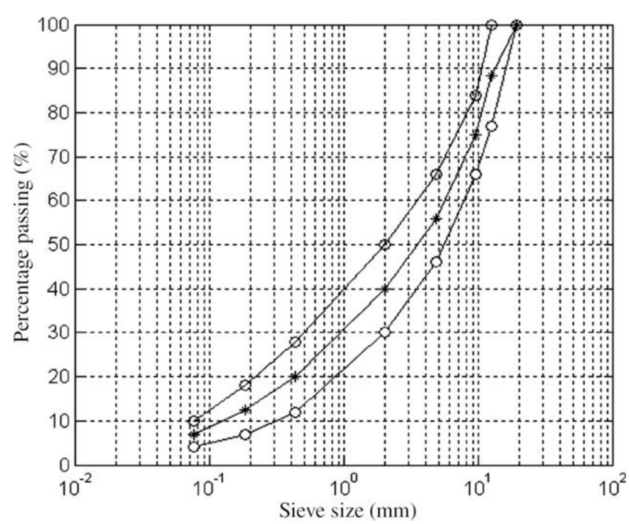

Fig. 1. Aggregate gradation.

Table 3
Physical properties of aggregate

Properties	Standard	Aggregate			
		Coarse	Fine	Filler	
				Limestone	Lime
Abrasion loss (%) (Los Angeles)	ASTM DC131	21	–	–	–
Frost action (%) (with Na_2SO_4)	ASTM C88	6.270			
Specific gravity (g/cm^3)	ASTM C127	2.652			
Water absorption (%)	ASTM C127	0.860			
Specific gravity (g/cm^3)	ASTM C128		2.668		
Water absorption (%)	ASTM C128		0.970		
Specific gravity (g/cm^3)	ASTM D854			2.704	2.440

neat bitumen and these mixtures also including 2% lime by total weight of aggregate (28.5% by weight of filler) and were represented by L. The last group of specimens prepared with SBS modified binder and also the mixtures including lime. In this group the lime percentage stands constant as 2% and the SBS content varies as 2%, 4% and 6%. The specimens in the final group were represented by LS2, LS4, LS6, respectively. The following tests were conducted on conventional, polymer modified, lime treated and lime + polymer treated mixes.

3. Test methods

3.1. Short-term ageing of binders

The ageing of asphalt mixtures occurs essentially in two phases, namely short- and long-term. Short-term ageing is primarily due to volatilization of the bitumen within the asphalt mixture during mixing and construction. Short-term laboratory ageing of the neat and SBS modified bitumen were performed by using the rolling thin film oven test (RTFOT, ASTM D2872). Standard ageing procedures such as 163 °C and 75 min for the RTFOT were used. The aged binders then subjected to penetration, softening point and dynamic shear rheometer tests to evaluate changes in their rheological properties.

3.2. Conventional binder tests

Penetration test at 25 °C, softening point and Fraass breaking point tests were performed according to ASTM D5, ASTM D36 and IP 80, respectively. Fraass breaking point was measured only for neat samples. Penetration index (PI) [19] was calculated from the following relationship:

$$(20 - \mathrm{PI})/(10 + \mathrm{PI}) = 50[(\log_{800} - \mathrm{pen})/(T_{\mathrm{SP}} - 25)], \tag{1}$$

where T_{SP} is the softening point (°C) and pen is the penetration at 25 °C.

3.3. Rotational viscosity test

A Brookfield viscometer (DV-III) was used for the viscosity tests on the neat and modified bitumen. The viscosity–temperature relationship was developed to determine the mixing and compaction temperature [20]. The rotational viscosity was determined by measuring the torque required to maintain a constant rotational speed (20 rpm) of a cylindrical spindle while submerged in bitumen maintained at a constant temperature.

3.4. Dynamic shear rheometer test

The dynamic shear rheometer (DSR) test was performed on all bitumens by using a Bohlin DSRII rheometer. This test was performed under controlled-stress loading (for neat binders 120 Pa and RTFOT residues 220 Pa) conditions at a constant frequency of 10 rad/s and temperatures between 52 and 82 °C with an increment of 6 °C. The tests were undertaken with a 25 mm diameter, 1 mm gap and parallel plate testing geometry.

The principal viscoelastic parameters obtained from the DSR were the complex shear modulus (G^*), and the phase angle (δ). G^* is defined as the ratio of maximum stress to maximum strain and provides with a measure of the total resistance to deformation when the bitumen is subjected to shear loading. G^* contains elastic and viscous components, which are designated as the storage modulus (G') and the loss modulus (G''). These two components are related to the complex shear modulus and to each other trough the phase (or loss) angle (δ) which is the phase, or time, lag between the applied shear stress and shear strain responses during a test. The phase angle defined above as the phase, difference between stress and strain in an oscillatory test is a measure of the viscoelastic balance of the material behavior. If δ equals 90° then the bituminous material can be considered to be purely viscous in nature, whereas δ of 0° corresponds to purely elastic behavior. Between these two extremes the material behavior can be considered to be viscoelastic in nature with a combination of viscous and elastic responses [21]. G^* and δ are used in two ways in the SHRP specifications. Permanent deformation is controlled by limiting $G^*/\sin\delta$ to at least 1000 Pa before ageing in RTFOT and at least 2200 Pa after ageing.

3.5. Marshall stability and flow test

Initially 48 Marshall specimens were prepared by using the standard Marshall hummer with 75 blows on each side of cylindrical samples at 5.2% bitumen content for the eight types (C, S2, S4, S6, L, LS2, LS4, LS6) of the specimens. The specimens were then divided in two groups consist of 24 mixtures, the average specific gravity of the specimens of the each group shall be equal. The first group of specimens was immersed in water at 60 °C for 30 min and then loaded to failure by using curved steel loadings plates along with a diameter at a constant rate of compression of 51 mm/min. The ratio of stability (kN) to flow (mm), stated as the Marshall quotient (MQ_1), and as an indication of the stiffness of mixes was determined. It is well recognized that the MQ is a measure of the materials resistance to shear stresses, permanent deformation and hence rutting [22]. High MQ values indicate a high stiffness mix with a greater ability to spread the applied load and resistance to creep deformation. The second group of specimens (conditioned specimens) was placed in water bath at 60 °C for 24 h. And then the same loading as described above was applied. The ratio of stability to flow of the specimens represented by MQ_2 was determined. The retained Marshall stability (RMS) was then found by using the average stability of each group using the following formula:

$$\mathrm{RMS} = 100(\mathrm{MS}_{\mathrm{cond}}/\mathrm{MS}_{\mathrm{uncond}}), \tag{2}$$

where RMS is the retained Marshall stability, $\mathrm{MS}_{\mathrm{cond}}$ is the average Marshall stability for conditioned specimens (kN) and $\mathrm{MS}_{\mathrm{uncond}}$ is the average Marshall stability for unconditioned specimens (kN).

An index of retained stability can be used to measure the moisture susceptibility of the mix being tested. A ratio of stabilities for "conditioned" specimens to "unconditioned" specimens is the criterion to identify a moisture susceptibility of a mix [23].

3.6. Indirect tensile stiffness modulus test

Stiffness modulus of asphalt mixtures measured in the indirect tensile mode is the most popular form of stress–strain measurement and considered to be a very important performance characteristic of the pavement. It is a measure of the load-spreading ability of the bituminous layers and controls the level of traffic induced tensile strains at the underside of the roadbase, which are responsible for fatigue cracking together with the compressive strains induced in the subgrade that can lead to permanent deformation. The indirect tensile stiffness modulus (ITSM) test defined by BS DD 213 [24] is a non-destructive test and has been identified as a potential means of measuring this property. The ITSM S_{m} in MPa is defined as

$$S_{\mathrm{m}} = F(R + 0.27)/(LH), \tag{3}$$

where F is the peak value of the applied vertical load (repeated load) (N), H is the mean amplitude of the horizontal deformation obtained from five applications of the load pulse (mm), L is the mean thickness of the test specimen (mm), and R is the Poisson's ratio (assumed 0.35). Twenty-four specimens were prepared for ITSM test. The test was done as deformation controlled via the universal testing machine (UTM). The magnitude of the applied force is adjusted by the system during the first five conditioning pulses such that the specified target peak transient diametral deformation is achieved. A value is chosen to ensure that the sufficient signal amplitudes are obtained from the transducers in order to produce consistent and accurate results. The value was selected as 7 mm in this test. During the test, the rise time, which is measured from when the load pulse commences and is the time taken for the applied load to increase from zero to a maximum value was set at 124 ms. The load pulse, application was equated to 3.0 s. The test was normally performed at 20 °C.

3.7. Indirect tensile strength test

In the indirect tensile strength test (ITS), cylindrical specimens are subjected to compressive loads, which act parallel to the vertical diametral plane by using the Marshall loading equipment. This type of loading produces a relatively uniform tensile stress, which acts perpendicular to the applied load plane, and the specimen usually fails by splitting along with the loaded plane. Based upon the maximum load carried by a specimen at failure, the ITS in kPa is calculated from the following equation:

$$\mathrm{ITS} = 2F/\pi LD, \tag{4}$$

where F is the peak value of the applied vertical load (repeated load) (kN), L is the mean thickness of the test specimen (m); D is the specimen diameter (m). The indirect tensile test was used for the determination of the asphalt concrete mixture moisture susceptibility according to ASTM D 4867 [25]. Resistance to moisture, and effect of SBS and lime on moisture-induced damage of asphalt concrete mixtures were evaluated. Totally 120 specimens were prepared for ITS test. Three unconditioned (dry) and three conditioned (wet) specimens were tested for each group of mixtures. Wet specimens were vacuum-saturated with distilled water so that 50–80% of their air voids were filled with water and then they were wrapped tightly with plastic film. The specimens were placed into a leak-proof plastic bag containing approximately 3 ml of distilled water. Wet specimens then were subjected to successive freeze–thaw cycling. One freeze–thaw cycle consists of freezing for 16 h at −18 °C, followed by soaking in a 60 °C water bath for 24 h. Different number of freeze–thaw cycles such as 1, 3, 5 and 7 were applied to mixtures to determine obviously the effects of SBS and lime on moisture damage. At the end of the each cycle the bag and the wrapping were removed and were placed in a water bath for 1 h at 25 °C before subjected to failure. The indirect tensile strength of dry specimens determined directly. Dry specimens only placed in a water bath for 1 h at 25 °C before subjected to failure. The indirect tensile strength ratio (TSR) was determined with following equation:

$$\mathrm{TSR} = 100(P_{\mathrm{cond}}/P_{\mathrm{uncond}}), \tag{5}$$

where P_{cond} is the indirect tensile strength of the wet specimens, P_{uncond} is the indirect tensile strength of the dry specimens. The TSR value must be higher than 0.70 after first freeze–thaw cycle according to ASTM D4867.

4. Results and discussion

4.1. Tests on binders

It can be seen from Table 1 that while the penetration is decreasing, softening point is increasing with the increase of SBS content. Due to ageing of binders with RTFOT method, the values of penetration decreased and the values of softening point increased. The relative temperature sensitivity of bitumens is often quantified by using the penetration index. The greater the PI is the less temperature sensitive is the material. The penetration index increased with the SBS content hence the temperature sensitivity of binders decreased. The increasing in retained penetration of binders after short term ageing process, and also the decreasing of the difference between softening point values before and after ageing, indicates that SBS reduces the ageing effects of binders.

In Fig. 2, the viscosity of binders was plotted against the temperature. The mixing and compaction temperatures were determined for each binder by using the 170 ± 20 and 280 ± 30 cP viscosity values, respectively. The values are given in Table 4. It has been recommended for the modified bitumens that the mixing and compaction temperatures must not exceed 180 °C in order to prevent damage in binder resulting from the excessive heating [12]. It was determined that the mixing temperature of 4% SBS modified binders and also the mixing and compaction temperatures of 6% SBS modified binders exceed the temperature of 180 °C. To prevent degradation the mixing and compaction temperatures of these binders were taken into account as 180 °C. Besides modification indices (η for modified bitumen divided by η for the neat bitumen) at 135 and 165 °C are presented in Table 4. Together with the penetration and softening point tests, the viscosities give a clear indication of the stiffening effect of SBS modification.

The DSR results and calculations showed that the values of rutting resistance parameter ($G^*/\sin\delta$) of SBS modified binders are higher than those of the neat bitumen at all test temperatures. The B 100–150 penetration bitumen meets the PG 64 specification requirements of SHRP ($G^*/\sin\delta$ 1000 Pa for non-aged and 2200 Pa for short term aged binder) as shown in Fig. 3 and Table 5. It is seen from Fig. 3 that the $G^*/\sin\delta$ parameter increased significantly with the increase of SBS content. The binder modified with 2% and 4% SBS meets PG 70 and 6% SBS meets PG 82, respectively. It was determined that the phase angle values decrease with the increase

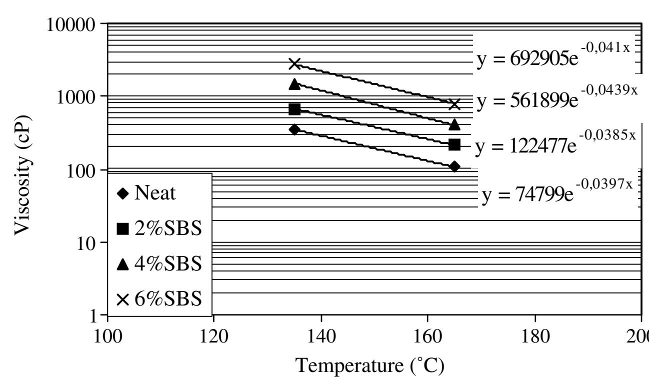

Fig. 2. Temperature viscosity relationship of binders.

Table 4
Mixing and compaction temperatures of mixtures and viscosity ratios of binders

Binder type	Mixing range (°C)	Compaction range (°C)	$\eta_{\mathrm{modified}}/\eta_{\mathrm{neat}}$ at 135 °C	$\eta_{\mathrm{modified}}/\eta_{\mathrm{neat}}$ at 165 °C
B 100–150	151–156	138–144	1.00	1.00
B 100–150 + 2% SBS	168–174	155–161	1.93	2.00
B 100–150 + 4% SBS	182–187	171–176	4.27	3.76
B 100–150 + 6% SBS	200–206	188–193	7.77	7.47

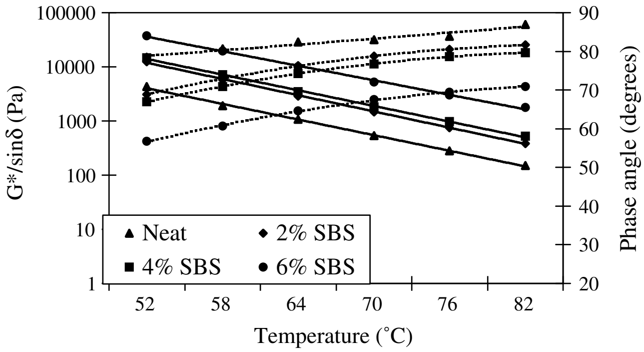

Fig. 3. The variation of $G^*/\sin\delta$ and phase angle with temperature.

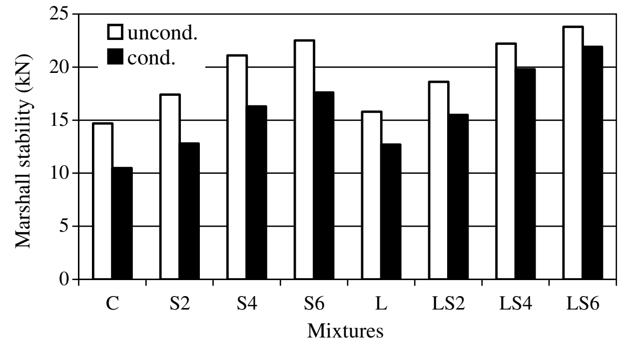

Fig. 4. Effects of SBS and lime on Marshall stability.

Table 5
$G^*/\sin\delta$ values of binders obtained from RTFOT residues

Binder type	Temperature (°C)	δ (deg)	$G^*/\sin\delta$ (Pa)
B 100–150	64	74.82	5300.23
B 100–150 + 2% SBS	70	65.00	10551.40
B 100–150 + 4% SBS	70	63.42	13064.50
B 100–150 + 6% SBS	82	65.84	6813.00

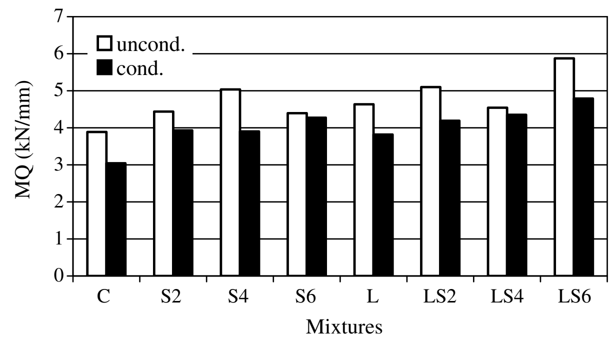

Fig. 5. Effects of SBS and lime on MQ values.

of SBS content at all temperatures hence the elastic properties increased.

4.2. Tests on bitumen aggregate mixes

4.2.1. Marshall stability and flow test

The Marshall stabilities and flows are given in Table 6 for each mixture. The values are the average of three samples. In Fig. 4 the relationship between Marshall stability and type of mixtures, in Fig. 5 the MQ values for both conditioned and unconditioned situation are given, respectively. It is seen that Marshall stability increases with the SBS content. It appears that the addition of SBS induce an increase in stiffness of binders. Thus the stability of mixtures containing SBS, results in higher values than those of control mixtures. It was determined that the Marshall stability values increased 8% by using only lime, 53% by adding 6% SBS and 62% by using lime and SBS together. On the other hand, the conditioned Marshall stability values increased 21% by using only lime, 68% by adding 6% SBS and 109% by using lime and SBS together. The latter indicates that the mixtures containing both SBS and lime are more resistant to moisture than expected.

In Fig. 5 it is seen that among the unconditioned mixtures containing only SBS, "S4" specimen has the highest MQ value. Among the lime treated mixtures "LS6" specimen gives the highest MQ values for both unconditioned and conditioned form. It is assumed that lime stiffen the specimens and prevent high flow so that provides high MQ. It is well recognized that the MQ is a measure of the material's resistance to shear stresses, permanent deformation and hence rutting.

In Fig. 6 the relationship between retained Marshall stability (RMS) and type of mixes are given. The RMS values increase with the SBS content for both conventional and lime treated mixtures. At the highest SBS content, the conventional mixtures have 78% retained Marshall stability, on the other hand lime treated mixture have 80% retained Marshall stability even without SBS. It can be assumed that addition of only 2% lime have approximately same effect with addition of 6% SBS with regard to moisture damage. Lime treated mixtures with SBS exhibited significant RMS values between 80% and 92%.

4.2.2. Indirect tensile stiffness modulus test

All types of specimens were subjected to indirect tensile stiffness modulus test (ITSM) at 20 °C. The average stiffness modulus

Table 6
Mixtures properties for Marshall test

Mixtures	Stability, 30 min at 60 °C, MS_1 (kN)	Flow, F_1 (mm)	MQ_1, MS_1/F_1 (kN/mm)	Stability, 24 h at 60 °C, MS_2 (kN)	Flow, F_2 (mm)	MQ_2, MS_2/F_2 (kN/mm)	RMS, MS_2/MS_1 (%)
Control	14.7	3.78	3.89	10.5	3.45	3.04	71.42
2% SBS	17.4	3.92	4.44	12.8	3.26	3.93	73.56
4% SBS	21.1	4.19	5.04	16.3	4.18	3.90	77.25
6% SBS	22.5	5.12	4.39	17.6	4.12	4.27	78.22
2% Lime	15.8	3.41	4.63	12.7	3.33	3.81	80.38
2% Lime + 2% SBS	18.6	3.65	5.10	15.5	3.70	4.19	83.33
2% Lime + 4% SBS	22.2	4.89	4.54	19.8	4.55	4.35	89.19
2% Lime + 6% SBS	23.8	4.05	5.88	21.9	4.57	4.79	92.01

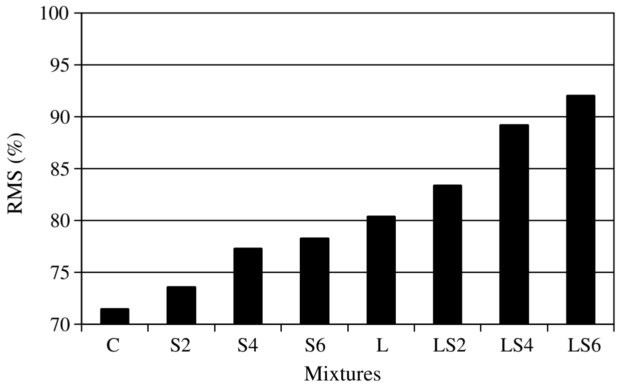

Fig. 6. Effects of SBS and lime on retained Marshall stability.

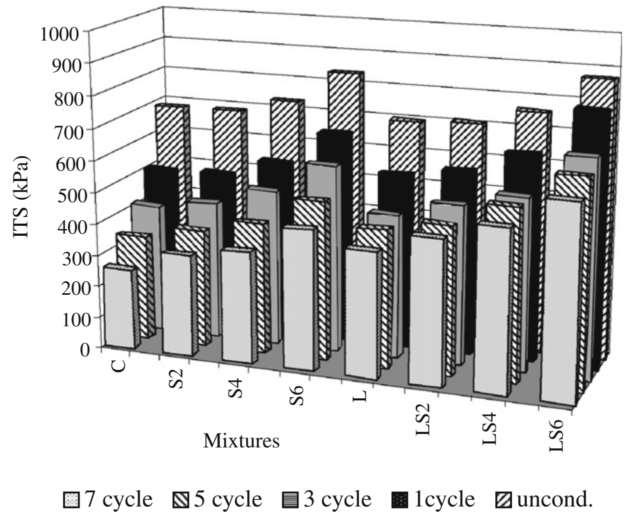

Fig. 8. Indirect tensile strength values of the mixtures under different freeze–thaw cycle.

results from eight different types of mixtures are given in Fig. 7. Each value was obtained from three specimens. The stiffness modulus of mixtures increased with increasing SBS content for conventional and lime treated mixtures. It was determined that the "S6" mixture has approximately two times higher modulus compared to those of the control mixture. The stiffness modulus of the "L" specimens, which include only 2% lime by weight of total aggregate, is approximately 12% higher than those of the control mixture. The "LS6" specimens have the highest modulus, which is 2.3 times higher than those of the control mixture.

4.2.3. Indirect tensile strength test

The indirect tensile strength of the mixture under different freeze–thaw cycles are given in Fig. 8. It is seen that the loss of indirect tensile strength of the lime treated mixtures due to freeze–thaw cycle is not as high as the mixture without lime. The decrease in indirect tensile strength could be attributed to the loss of adhesion of the mixture and/or cohesion of binder. It can be conclude from the Fig. 8 that adding SBS and lime together to mixtures, improves the adhesion and cohesion of binder and do not allow the displacement of asphalt components from the aggregate surface easily by water thus provides more reasonable mixtures than only lime treated mixtures.

Fig. 9a shows the tensile strength ratio for specimens that were prepared with different SBS contents after different freeze–thaw cycles. It is seen that the tensile strength ratio for all mixtures decreases regularly as the number of freeze–thaw cycles increases, and also TSR values increase comparatively with the SBS content. The "S6" specimen have the highest TSR value as 0.79 at first cycle, and this specimen lost its TSR value approximately 33% at the end of the 7th cycle. None of the specimens have a TSR higher than 0.8 even at the first cycle in this group.

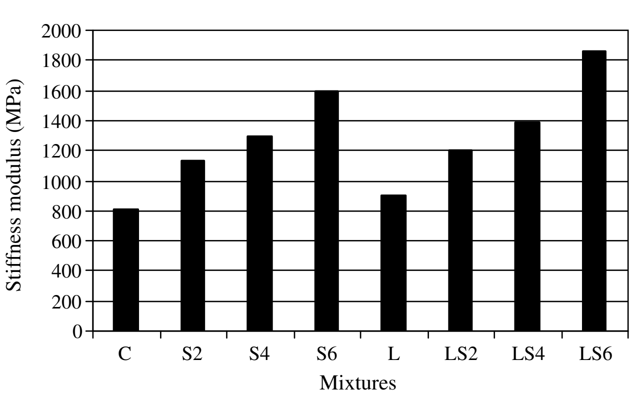

Fig. 7. The indirect tensile stiffness modulus of mixtures.

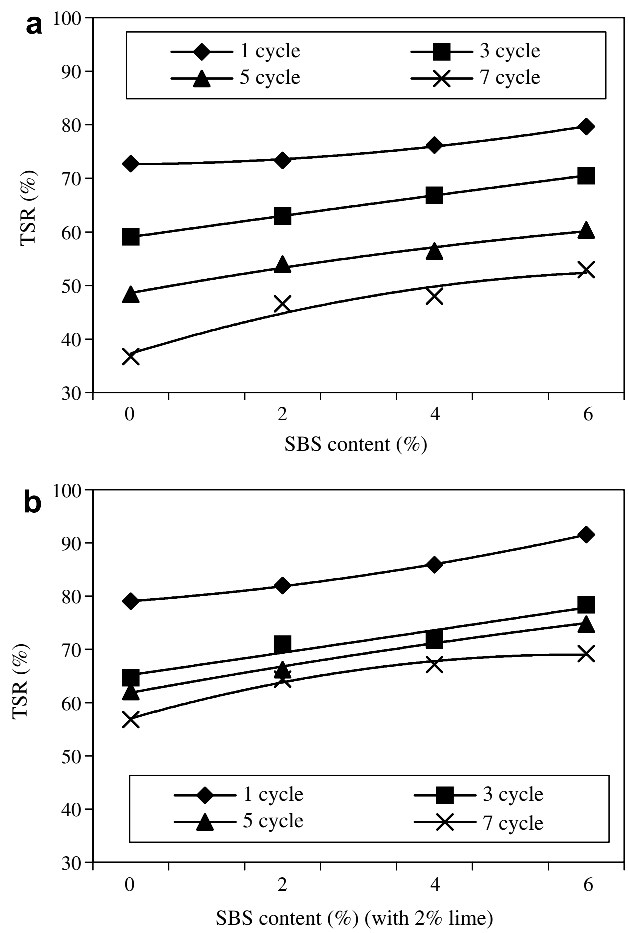

Fig. 9. Impact of freeze–thaw cycle and SBS on tensile strength ratio of pure and lime treated mixtures.

Fig. 9b shows the tensile strength ratio for specimens that were prepared with different SBS content and with 2% lime after different freeze–thaw cycles. It is seen that the TSR values increases comparatively with the SBS content, however, the decrease in TSR values of the specimens with the increase of freeze–thaw cycles is not regularly. It means that the lime affects significantly the TSR values of the mixtures.

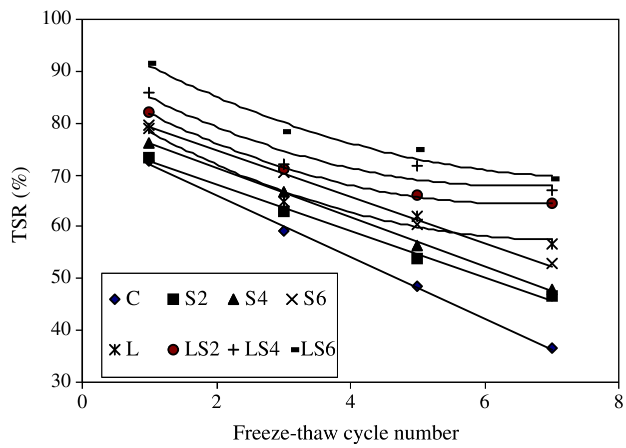

Fig. 10. The variation in the TSR of the mixtures under different freeze–thaw cycle.

The variation in the TSR of the mixtures under different freeze–thaw cycles is given in Fig. 10. It was determined that the TSR values of the mixtures containing only SBS decreased straightly while the TSR value of the lime treated mixture was decreasing unlinearly. As seen from the figure that the TSR value of only SBS modified mixtures is quickly reducing at the first freeze–thaw cycle but the lime treated mixtures continue to decline in a slower rate. It was also determined that only the "LS6" mixture retains a reasonably high tensile strength ratio (approximately 0.70) after seven freeze–thaw cycle. The "LS4" mixture maintains 0.70 TSR until 7th cycle, "LS2" maintain until 5th cycle and "L" mixture maintains 0.70 TSR until 3rd cycle. The TSR values of lime treated mixtures are higher than those of the 6% SBS modified mixtures at the end of the 7th period. These results indicate that the lime is more effective than SBS regarding moisture damage.

5. Conclusion

The objectives of this study were to evaluate the effects of SBS and lime as mineral filler in hot mix asphalt. Various laboratory tests were used to evaluate the characteristics of hot mix asphalt by varying contents of SBS and a constant rate of lime. Based on the laboratory test results, the following conclusions were drawn:

- Penetration, softening point, high temperature viscosity and DSR tests have proved that the SBS content increased the stiffness. The penetration index of SBS modified binders increases with the increase in SBS level. This suggests that the addition of SBS, contributes to reduction in the brittleness and temperature sensitivity of the binder. Rutting resistance parameter $G^*/\sin\delta$, according to SHRP specifications, increased with SBS content at all test temperatures.
- In the Marshall stability test, Marshall stability values increased with the SBS content before and after conditioning. The stability of unconditioned lime treated mixtures was approximately 8% higher than those of the unconditioned control mixture. However this value increased up to 21% for the conditioned mixtures. According to retained Marshall stability, it was concluded that the addition of only 2% lime had approximately same effect with addition of 6% SBS with regard to moisture damage.
- In the indirect tensile stiffness modulus tests the improvement effect of lime was not so high because of the test was performed in an unconditioned situation. However lime stiffened the mixtures and the specimens prepared with 2% lime and 6% SBS had the highest modulus, which is 2.3 times higher than those of the control mixture.
- In the indirect tensile strength test, it was obtained that the decrease in TSR values of the only SBS modified mixtures with the increase of freeze–thaw cycles was steady, however the decrease in TSR values of the lime treated mixtures with the increase of freeze–thaw cycles was not steady. It means that the lime significantly improves the TSR performance of the mixtures. It was determined that the mixtures made with 2% lime and 6% SBS showed the least reduction in TSR and only these mixtures maintained a reasonably high tensile strength ratio (approximately 0.70) after seven freeze–thaw cycle. Even at the end of the 7th period, the TSR value of the mixtures including 2% lime and 6% SBS was higher than 0.70, which is the lower limit in ASTM D4876.
- Based on the laboratory test results, it was concluded that the addition of lime and SBS together in hot mix asphalt exhibited high accordance and significantly improves the performance of mixtures especially the resistance to moisture damage. It is also considered that in the cases in which SBS and lime used together, the premature permanent deformation alongside the moisture damage can be prevented.

References

[1] Terrel RL, Al-Swailmi S. Water sensitivity of asphalt–aggregate mixes: test selection. SHRP-A-403, Strategic highway research program. Washington (DC): National Research Council; 1994.

[2] Epps JA, Sebeally PE, Penerande J, Maher MR, Hand JA. Compatibility of a test for moisture induced damage with superpave volumetric mix design. National cooperative highway research program, Report no. 444. Washington (DC); 2000.

[3] Sengoz B, Agar E. Effect of asphalt film thickness on the moisture sensitivity characteristics of hot mix asphalt. Build Environ 2007;42:3621–8.

[4] Kandhal PS. Moisture susceptibility of HMA mixes: identification of problem and recommended solutions. National Asphalt Pavement Association Quality Improvement Publication (QIP); 1992. p. 119.

[5] Roque R, Birgisson B, Drakos C, Sholar G. Guidelines for use of modified binders. Florida Department of Transportation, Project number: 4910-4504-964-12; 2005.

[6] Paul HR, Compatibility of aggregate, asphalt cement and antistrip material. Ltrc research project no. 85-1b. Ltrc report no. 292.

[7] Jones GM. The effect of hydrated lime on asphalt in bituminous pavements. National lime association (NLA) meeting, Utah DOT; 1997.

[8] Little DN, Epps JA. Hydrated lime in hot mix asphalt. Presentation manual. FHWA-HI-93-032. FHWA, AASHTO, and National Lime Association (NLA); 1993.

[9] Maupin GW. Effectiveness of antistripping additives in the field. Virginia Department of Transportation, Report no. VTRC 96-R5. Richmond; 1995.

[10] Abo-Qudais S, Al-Shweily H. Effect of antistripping additives on environmental damage of bituminous mixtures. Build Environ 2007;42:2929–38.

[11] Isacsson U, Lu X. Testing and appraisal of polymer modified road bitumens – state of the art. Mater Struct 1995;28:139–59.

[12] Cortizo MS, Larsen DO, Bianchetto H, Alessandrini JL. Effect of the thermal degradation of SBS copolymers during the ageing of modified asphalts. Polym Degrad Stab 2004;86(2):275–82.

[13] Tayfur S, Ozen H, Aksoy A. Investigation of rutting performance of asphalt mixtures containing polymer modifiers. Constr Build Mater 2007;21:328–37.

[14] Vlachovicova Z, Wkumbura C, Stastana J, Zanzotto L. Creep characteristics of asphalt modified by radial styrene–butadiene–styrene copolymer. Constr Build Mater 2007;21:567–77.

[15] Isacsson U, Zeng HY. Relationships between bitumen chemistry and low temperature behavior of asphalt. Constr Build Mater 1997;11(2):83–91.

[16] Shuler S, Douglas I. Improving durability of open-graded friction courses. Transport Res Rec 1990;1259:35–41.

[17] Won MC, Ho MK. Effect of antistrip additives on the properties of polymer-modified asphalt binders and mixtures. Transport Res Rec 1994;1436:108–14.

[18] Huang SC, Robertson RE, Branthaver JF. Physico-chemical characterization of asphalt–aggregate interactions under the influence of freeze–thaw cycles. TRB annual meeting; 2003.

[19] Read J, Whiteoak D. The shell bitumen handbook. 5th ed. UK: Shell Bitumen; 2003.

[20] Bahia HU, Recommendations for mixing and compaction temperatures of modified binders. Draft topical rep. for NCHRP study no. 9–10. Washington (DC); 2000.

[21] Airey GD. Rheological evaluation of ethylene vinyl acetate polymer modified bitumens. Constr Build Mater 2002;16:473–87.

[22] Zoorob SE, Suparma LB. Laboratory design and investigation of the properties of continuously graded asphaltic concrete containing recycled plastics

aggregate replacement (plastiphalt). Cement Concrete Compos 2000;22:233–42.
[23] Aksoy A, Samiloglu K, Tayfur S, Ozen H. Effects of various additives on the moisture damage sensitivity of asphalt mixtures. Constr Build Mater 2005;19:11–8.
[24] British Standards Institution. Method for the determination of the indirect tensile stiffness modulus of bituminous mixtures. Draft for development DD-213; 1993.
[25] American Society for Testing and Materials. Standard test method for effect of moisture on asphalt concrete paving mixtures. D 4867/D4867M-96.